GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No. A-57-613 (R6019-0A0) GTRC/GIT DATE 9 / 6 / 85

Project Director: Dr. A. P. Sheppard School/Lab VPR

Sponsor: Whirpool Corporation

Type Agreement: Agreement dated 8/7/85

Award Period: From 7/1/85 To 6/30/86 (Performance) 6/30/86 (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$ 76,176	$ 76,176
Funded:	$ 76,176	$ 76,176

Cost Sharing Amount: $ None Cost Sharing No: N/A

Title: Home Appliance Robotics Research

ADMINISTRATIVE DATA

OCA Contact Brian J. Lindberg X4820

1) Sponsor Technical Contact:

Dr. W. Wale Cutler, Staff VP
University Relations
Whirpool Corporation
The Elisha Gray II Research
and Engineering Center-Monte Road
Benton Harbor, MI 49022

2) Sponsor Admin/Contractual Matters:

Same as 1)

Defense Priority Rating: N/A

Military Security Classification: N/A

(or) Company/Industrial Proprietary: N/A

RESTRICTIONS

See Attached N/A Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with Sponsor. All purchase of Special Items of Equipment in excess of $500 must be approved in writing by Sponsor.

COMMENTS:

Continuation of Project A-57-606.

COPIES TO:

SPONSOR'S I. D. NO. 03.222.000.85.001

Project Director	Procurement/GTRI Supply Services	GTRC
Research Administrative Network	Research Security Services	Library
Research Property Management	Reports Coordinator (OCA)	Project File
Accounting	~~Research Communications (2)~~	Other Jones

GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date Dec. 8, 1987

Project No. A-57-613 School/~~Lab~~ VPR

Includes Subproject No.(s) N/A

Project Director(s) A. P. Sheppard GTRC / ~~GIT~~

Sponsor Whirlpool Corp.

Title Home Appliance Robotics Research

Effective Completion Date: 6/30/86 (Performance) 6/30/86 (Reports)

Grant/Contract Closeout Actions Remaining:

- [x] None
- [ ] Final Invoice or Final Fiscal Report Already submitted
- [ ] Closing Documents
- [ ] Final Report of Inventions
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

Continues Project No. A-57-606 Continued by Project No.

COPIES TO:

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GTRC
Research Communications (2)
Project File
Other Duane Hutchison
Angela DuBose
Russ Embry

FORM OCA 69.285

A-57-613A-57-613

GEORGIA TECH RESEARCH CORPORATION

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332-0420

Telex: 542507 GTRCOCAATL
Fax: (404) 894-3120

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Refer to: JG/03.222.000.87.001

July 10, 1986

A-57-613/Sheppard

Whirlpool Corporation
Monte Road
Benton Harbor, MI 49022

Attention: Dr. W. Gale Cutler

Subject: Home Appliance Robot Research
(GTRC Project No. A-57-613)

Dear Dr. Cutler:

Enclosed is the annual report for the Home Appliance Robot Research program for the year ending 30 June 1986. Also enclosed is a budget for work proposed for the next year. Georgia Tech Research Corporation respectfully requests that the Sponsored Research Agreement dated 7 August 85 be amended to authorize an additional $81,789 for continuation of the project through 30 June 86.

We appreciate the opportunity to perform this research for Whirlpool. If you have any questions, please contact us at your convenience. Technical matters should be referred to Dr. Sheppard at 404/894-4826. Please contact me at 404/894-4817 to discuss contractual matters.

Sincerely,

Jerry Goldbaugh
Contracting Officer

JG/sdm

Addressee: Three (3) copies

GEORGIA TECH 1885-1985

DESIGNING TOMORROW TODAY

Georgia Institute of Technology
Office of Vice President for Research
Centennial Research Building
400 Tenth Street, N.W.
Atlanta, Georgia 30332

July 9, 1986

Dr. W. Gale Cutler
Staff Vice President
University Relations
Whirlpool Corporation
Monte Road
Benton Harbor, MI 49022

Dear Gale:

Attached you will find the annual report for our Home Appliance Robot Research along with tests and budget for continuation for the next year. We believe with our recent progress that we are in an excellent position to furnish a demonstration unit to Whirlpool by June 30, 1987. We think the additional expenditure is warranted to insure maximum return value to Whirlpool, in that much favorable publicity could be obtained, in addition to the technology acquired.

Please do not hesitate to call Brett, Tom, or me if you have any questions or need further information. We look forward to a continued research relationship with you and Whirlpool.

Sincerely yours,

Albert P. Sheppard
Associate Vice President
for Research

APS/bc
Enclosure

WHIRLPOOL HOME APPLIANCE ROBOT RESEARCH
ANNUAL STATUS REPORT
JULY 1985 -- JUNE 1986

by

Albert P. Sheppard, Brett Lapin and Thomas Single
Office of Vice President for Research
Georgia Institute of Technology
Atlanta, Georgia 30332

Introduction

The current research period, July 1985 through June 1986, has been very productive for the mobile robot project. During this year there was considerable enhancement of the unit constructed in the previous research period and the construction of a second unit. Research progress has been made in the solution of several very general problems for navigation of the mobile vehicles. These solutions are related to the movement algorithms on the two robots for covering a region and for absolute positioning of the vehicle. Solutions to both of these problems were required before an appliance carrying robot could be constructed.

The original Hero style ultrasonic guidance sub-system and the teach/repeat sub-system were originally scheduled to be integrated into a sturdy, autonomous floor cleaner during this research period; however it was found that the teach/repeat sub-system could not track a path within the required error limits for successful navigation of a region with obstacles. The problems were due to uncontrollable errors: wheel slippage, uneven floor surfaces, changes in floor surfaces, backlash in the gear motors, and sideways creep from rug knap.

The original ultrasonic guidance sub-system was not designed to overcome these errors; therefore, the teach/repeat sub-system had to be enhanced to cope with these problems before integration. The need for this enhancement combined with the need to upgrade the perimeter tracking sub-system required that we keep the two sub-systems separate. Integration of the two sub-systems onto a single vehicle was delayed until a reliable vehicle could be attained.

During the past research period, the following specific accomplishments were realized in the mobile robot project:

(a), The construction of a sensor-based test-bed mobile robot, named "Zamboni", which is capable of operation independent of power cords.

(b), The development of an ultrasonic guidance sub-system and associated region covering software which could be the basis for the area navigation system needed to control an autonomous floor cleaner.

(c), Installation and successful testing of the ultrasonic guidance sub-system and the associated region covering algorithm on Zamboni.

(d), Enhancement of the computer-based robot constructed last year, named "Pete", including the following:

- development of an absolute positioning sub-system based on an optical scanner to overcome the teach/repeat sub-system limitations, as well as to aide in robot guidance,

- development of a path optimization algorithm which finds the shortest path through a multi-obstacle region,

- addition of voice recognition to yield another option for direct robot control and

- addition of voice synthesis for robot-to-user interfacing (for example, a smoke alarm warning which was implemented on Pete).

(e), Both Zamboni and Pete were given full CRT screens for interaction with humans.

These advancements greatly enhanced the capabilities of the mobile robots. The following is a synopsis of each of the above developments.

Sensor-based Test-bed Mobile Robot Construction

The structural design of Zamboni is virtually identical to Pete in order to facilitate the integration of the two systems onto a single frame. There are two main differences between the structure and operation of these robots and the Hero 1.0 robot: the D.C. motors of Zamboni and Pete yield much more accurate tracking and raise totally new design considerations over the stepper motors of Hero robot, and the computation needs of Zamboni and Pete are served by an IBM-PC computer (Intel 8088 based) as compared to the lesser capabilities of Hero's MC6808 microprocessor.

Region Covering System

The ultrasonic guidance sub-system was designed to enable Zamboni to navigate through any rectangular region of arbitrary size with vertical boundaries, such that all areas of the region are "covered" (i.e., the wheels track over every portion of the region). In its current form, the navigation system can guide the robot through the rectangularly shaped region (without obstacles) completely covering the bounded area. The rectangularity constraint is needed because the current algorithm cannot adapt for any stray parts of a region which has not been covered. (E.g. Any triangular part of the region left over after the central rectangular portion has been completed.) The ultrasonic guidance sub-system, as installed on Zamboni, utilizes the following:

* four ultrasonic sensors to measure orientation to and distance from the vertical boundaries,

* a steering potentiometer to measure steering wheel deflection

* custom designed control and interface hardware and,

* an IBM-PC to supervise the entire system.

The software is written in "C". The control and interface hardware consisted of the following: hardware to interface the computer and control signals to the drive and steering motors, hardware to create the correct control signals for the orientation algorithm - the basis for robot orientation, and hardware to control the ultrasonic sensors - triggering them at the correct time as well as interpreting the return signals for distance measurements.

The design employs two modes of operation. The first mode requires Zamboni to track a boundary as well as keep itself a certain distance from this boundary - the distance will depend on where the robot is in its routine. The second mode of operation involves making Zamboni know how and when to cover the interior sections of the region. The orientation algorithm, which orients the robot to the boundary and its placement in the region, is the same algorithm as that described for the perimeter-tracking sub-system in our proposal/update dated June 5, 1985. However, as mentioned earlier, the distance that Zamboni tracks a certain boundary depends on where the robot is in its routine.

The new algorithm allows Zamboni to completely cover a rectangular region of any size by calculating a path through the region. The general strategy of the algorithm is one of using two left side sensors to detect distance from a boundary wall and to keep the robot on a path parallel to the same boundary wall.

This is essentially the perimeter tracking algorithm developed in last year's research. Superimposed on the perimeter algorithm is a path calculation algorithm which guides Zamboni in a rectangular path with one side of the rectangle exactly one half of one side of the rectangular region to be covered. This divides the region to be covered into two equal regions. The rectangular path is then displaced one sweeper width for each traverse of the path until the region is completely covered. Figure 1 is a diagrammatic representation of the algorithm. This control strategy only uses left side sensors and right hand turns in the algorithm.

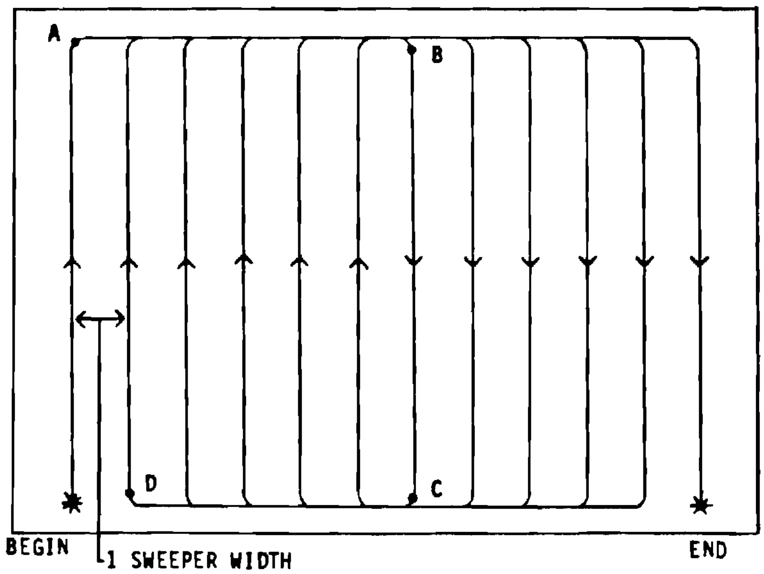

Figure 1.

Zamboni starts in any corner of the region. As the robot moves along the first boundary wall, the two left side ultrasonic sensors provide position data to the guidance program. The guidance program controls the front steering wheel to maintain a constant 12-inch distance from the boundary wall as Zamboni moves toward the second boundary wall. (This 12-inch distance is adjustable in the software down to 8 inches.)

Simultaneously, the front ultrasonic sensor measures the distance from the second boundary wall. When Zamboni approaches to within 12 inches of the second boundary wall (see Position A, Figure 1), the guidance program directs the robot to stop, then turn 90 degrees to the right. After completing the turn, the two left side sensors again track the boundary wall to the robot's left while the front and rear sensors measure the distance from the third and first boundary wall, respectively.

The guidance program detects the midpoint of the second boundary wall by locating the position where the distance to the third boundary wall, as measured by the front sensor, is equal to the distance from the first boundary wall, as measured by the rear sensor. (See Position B, Figure 1.) When the midpoint is detected, Zamboni stops and turns 90 degrees to the right. Zamboni then tracks a path down the center of the region toward the fourth boundary wall using position data relative to the third boundary wall from the two left side sensors. The front sensor constantly measures the distance to the fourth boundary wall as the robot moves down the center of the region.

When Zamboni is within 12 inches of the fourth boundary wall (see Position C, Figure 1), the robot stops, turns 90 degrees to the right until the two left side sensors can properly detect the fourth boundary wall. The robot then moves along the fourth boundary wall, using data from the left side sensors to maintain a constant 12-inch distance from the fourth boundary wall. Simultaneously, the front sensor measures the distance to the first boundary wall. When Zamboni approaches to within 12 inches plus one sweeper width of the first boundary wall (see Position D, Figure 1), the robot stops and turns 90 degrees to the right so that the two left side sensors can again acquire distance measurements from the first boundary wall. At this point in the routine, Zamboni has completed one revolution of the region. As Zamboni begins the second revolution of the region, the robot again tracks relative to the first boundary wall, but this time the path is 12 inches plus one sweeper width away from the first boundary.

Zamboni continues to track a constant perimeter rectangular path with each path displaced one sweeper width toward the third boundary wall. When the front sensor detects that Zamboni is within 12 inches of the third boundary wall, the robot has covered the region and thus begins its terminal sequence. The robot will turn 90 degrees to the right then track the third boundary wall using data from the left side sensors, until the front sensor detects the position of the robot is within 12 inches of the fourth boundary wall. Zamboni then turns 90 degrees and terminates its algorithm.

Absolute Positioning Sub-system

The method for obtaining the absolute position of Pete in a bounded region is accomplished by using an optical scanner. The optical scanning sub-system that was developed consisted of an infra-red emitter-detector pair mounted on top of Pete with a mirror mounted at a 45 degree angle in a rotating frame above the detector. Retroreflective strips from 3M were placed at three arbitrary corners of a region with the dimensions of the region preprogrammed into the robot. By measuring the angles between the reflected beams in terms of time with respect to the scanner, Pete is able to compute where it is within a known region. When tested, it was found that not enough infrared power was being returned from the reflective strips to detect the needed distances using the required speed of rotation. As a temporary measure to get test data, lights were placed in the three corners of the region which gave a return of sufficient energy to the detectors for reliable operation.

The optical scanner was designed to rotate at a speed of 300 revolutions per minute which provides a resolution of 2.4 inches per revolution when Pete travels at a speed of 12 inches per second. Since the tests performed were run with Pete traveling at approximately 4 inches per second, the resolution was somewhat better than this minimum design criterion. Since the resolution of the optical scanner is dependent on the rotation speed of the scanner, the current mechanical limitations on the scanner sub-system limit the resolution of Pete's positioning algorithm. The detection circuitry itself is theoretically capable of reliable detection when scanning at approximately 600,000 revolutions per minute which is far beyond the practical accuracy or the mechanical performance needed. The resolution could be greatly improved by reducing the scanner size and weight and by more accurate balancing of the entire rotating mechanism so that a faster motor can be used. Such an effort is currently under way.

The software developed to complement this scanning sub-system was written in "C" and used all of Pete's existing control software and hardware for the drive and steering sub-systems from last year's project. As the robot is moving through the room, the software polls the scanner hardware for the counters when ready and reads them. After it gets the counts for a complete revolution, it computes the X and Y coordinates using the dimensions of the room and the angles between the lights. Thus Pete can determine its current location in the region. A diagrammatic representation of the optical scanning sub-system can be seen in Figure 2.

The optical scanner sub-system proved to be very accurate. While Pete was stationary, the sub-system maintained a resolution of 0.001 feet but, of course as Pete moved, the resolution was reduced. In order to test Pete's accuracy over a path, additional software was developed to navigate through the desired path. The method used was to compute the slope of the line between the starting point and the desired end point and constantly compare the slope of the line between the current point and the desired end point to that of the original slope. As Pete got closer to the end point, the error between the two slopes was proportionately greater for points the same distance from the original line. This enabled Pete to track a straight line path with only minor oscillations about the desired track line between the two end points. This method of control worked with reasonable accuracy, however, we would like to improve the accuracy of the tracking so alternative approaches are currently being investigated to achieve better accuracy.

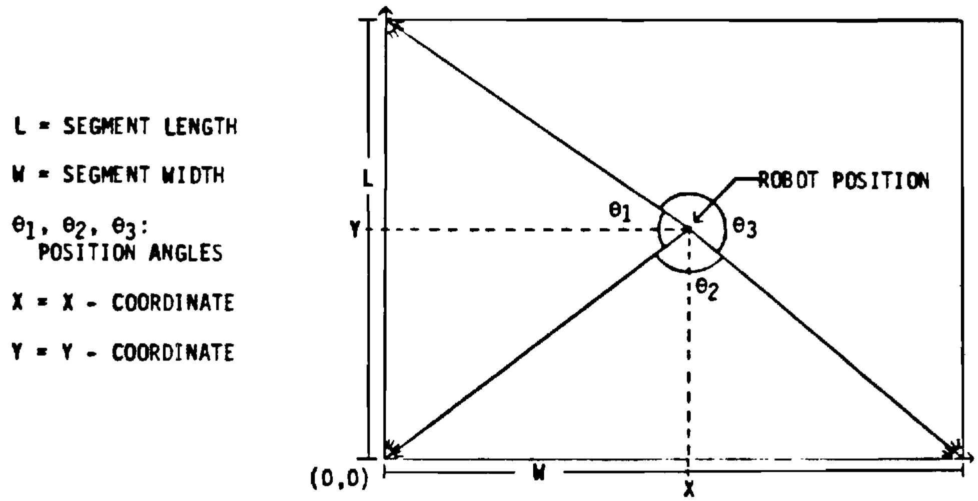

Figure 2.

Path Optimization Algorithm

Path optimization software was developed to compute the shortest path between any two points in a room with <u>a priori</u> knowledge of the obstacles in the room. In order for Pete to know where all obstacles are within the room, the user must program a map of the room into the computer using an invariate (x,y) coordinate system. The room is represented in matrix form and then a modified Dijkstra algorithm is applied to this room to find the shortest path between the robot's present position and the desired end position. This method gives the shortest path with only 90 and 45 degree turns; however, the path can be further shortened by using a smoothing algorithm which allows turns of any angle. Again, this software is written in "C" and was developed on a Masscomp workstation.

In the original version of the obstacle software, each time Pete needed to calculate the optimum path, the program on the Masscomp was used. The user inputted the start and end points into the Masscomp computer, then the program would read the data file for the particular room to learn the position of the obstacles and compute the optimum path. The path sequence was then downloaded to the IBM-PC via an RS-232 connection.

The program was optimized and the compiled size reduced so that it can now be executed in the limited memory constraints of the IBM-PC mounted on Pete. Pete now has the capability to make the path optimizing computations on board without resorting to outside assistance from the Masscomp. This will now make it possible for Pete to be completely autonomous in its operation.

A summary of the program strategy for calculating the optimum path from arbitrary point A to arbitrary point B through a region containing obstacles at known locations in the region is as follows:

(a), The user inputs the starting point, the ending point, and the name of the room for which the path is to be calculated.

(b), The program reads the file containing the locations of all obstacles of the desired room and creates a matrix to represent that room internal to the program.

(c), All obstacles are expanded by half the width of Pete. This allows the simplifying assumption that the robot can be represented as a single point in all computations.

(d), The software computes the shortest path from A to B avoiding all obstacles using a modified Dijkstra algorithm.

(e), The path is smoothed to reduce the number of turns in the path. The principal of this smoothing operation is to utilize the capability of the steering motor to turn Pete at any angle and eliminate any unnecessary turns calculated by the path optimizer due to the constraint of allowing only 90 degree and 45 degree turns.

(f), The IBM-PC initializes all control circuits.

(g), The control software computes the angle of rotation needed to orient Pete in the direction of the first segment of the path.

(h), Pete is rotated to the first segment.

(i), Pete drives along the path segment using the absolute positioning sub-system to maintain the robot path along the straight line path segment until it reaches the end of the segment.

Pete navigates a complete path by repeating Steps "g" through "i" for each segment of the smoothed path computed in Step "e". This method works well using the current absolute positioning sub-system control strategies.

Because of battery problems, the full algorithm has not been tested completely. In the next series of tests, we expect Pete to be able to navigate through a room avoiding known, fixed obstacles very accurately.

Voice Recognition

The capability of voice input was added to yield a powerful option for direct control of the robot. The voice recognition sub-system uses a Tecmar recognition board in the PC. It can be used to control the general motion of the robot, or to control the teach mode instead of the teach pendant. This enables the user to give commands to the robot without getting near it. As such it could be used as a safety measure so that the user could stop the robot without any contact with it.

Voice Synthesis

A voice synthesis sub-system was developed to facilitate robot communication with the user. The sub-system was designed using a Digi-Talker synthesis chip and the standard vocabulary ROMs to accompany it. This voice capability allows the robot to warn the user when it is doing something or if it detects something that the user should know about. This can be used with the smoke detector that is used on the robot. Hardware was developed to interface a smoke detector with the on-board PC. When the detector detects smoke, it causes an interrupt in the control program and alarms the user that there is smoke present. The on-board voice could be used as an interface with the user unless the user is near the robot, in which case the on-board screen display could be used.

Future Developments

The research from the past year unquestionably has laid the ground work for the development of a prototype mobile robot capable of vacuuming an area containing commonly placed, uniform geometry obstacles of the home. Some of the enhancements and new developments which need to take place to achieve the above result are as follows:

(a), The region covering system requires the capability of completely covering a region of diverse shape.

(b), The guidance sub-system needs to be updated to include obstacle detection and recognition capabilities.

(c), A region mapping sub-system must be developed to give the robot the capability of perceiving region shape and obstacle placement with a minimum of pre-programming.

(d), Software needs to be developed to generate a region covering strategy relative to the region perceived by the mapping sub-system. The software will specifically be designed to perform the task of "vacuuming" a room containing a limited number of obstacles.

(e), A memory sub-system is needed to retain the current strategy and its status (i.e., the robot needs not only to know where it is going in the future, but it must also retain history to know what has been completed.)

Our aim for the next research year is to develop a prototype, demonstration robot, capable of autonomously simulating the cleaning of floors. This demonstration robot will have the capability of entering a room, perceiving the room layout, planning a cleaning strategy, executing the cleaning strategy, and interacting with humans using voice recognition and synthesis over a small, simple vocabulary. The integration of the research accomplished so far with the projected enhancements listed above would produce an autonomous floor cleaner.

A budget for the proposed continuation of the project is attached. Dr. Sheppard and Messrs. Lapin and Single will continue as the principal project participants.

Proposed Budget to Whirlpool Corporation
July 1, 1986 - June 30, 1987

Home Appliance Robotics Research

Direct Costs:

Research Engineer I, 1 man year	$34,000	
Fringe benefits @ 23.6% of salaries	8,024	
Sub-total	$42,024	
Materials, supplies and equipment	6,000	
Travel	2,000	
Sub-total	$50,024	
Indirect Costs @ 63.5% of direct costs	$31,765	
Grand Total		$81,789